Numerical simulations of the accretion process in Kerr space-times with arbitrary value of the Kerr parameter

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Abstract

According to the Cosmic Censorship Conjecture, all the singularities produced by the collapsing matter must be hidden behind an event horizon. In 4D general relativity, this implies that the final product of the collapse is a Kerr-Newman black hole. Here I consider the possibility that the Cosmic Censorship Conjecture can be violated. I present the results of some numerical simulations of the accretion process onto Kerr black holes (objects with event horizon) and Kerr super-spinars (fast-rotating objects without event horizon). This is a preliminary study to investigate how the Cosmic Censorship Conjecture can be tested by astrophysical observations.

1 Introduction

Today gravity is relatively well tested in the weak field limit, while little or nothing is known when it becomes strong [1]. Strong gravitational fields can be found around astrophysical compact objects and could be probed by studying the radiation emitted in the accretion process. However, that turns out to be a very difficult job: the radiation emitted by the falling gas depends significantly on the accretion model and it is apparently impossible to constrain gravity without several model-dependent assumptions. For such a reason, today we know some "black hole candidates", but actually we do not know if these objects have an event horizon or if the space-time around them is described by the Kerr metric. In astrophysics, one assumes that these candidates are Kerr black holes and studies different scenarios of accretion in order to explain observations. Here I am instead interested in testing the actual nature of these objects. In particular, I consider the possibility that some black hole candidates rotate too fast to have an event horizon and I show that the accretion process onto them would be so much different that hopefully future theoretical studies and astrophysical observations will be able to confirm or rule out such a possibility.

2 The Cosmic Censorship Conjecture

In general relativity, under apparently reasonable assumptions, the collapsing matter leads inevitably to the formation of singularities. Here there are two possibilities: *i*) the singularity is hidden behind an event horizon and the final product is a black hole, *ii*) the singularity is not hidden behind an event horizon and therefore is naked. Since space-times with naked singularities typically have pathologies, usually some form of the Cosmic Censorship Conjecture is assumed and naked singularities are forbidden [2]. Neglecting the electric charge, it turns out that, in four dimensions, the final product of the gravitational collapse of matter is a Kerr black hole [3, 4].

The Kerr metric is completely characterized by two parameters; that is, the mass M and the spin J. The latter is often replaced by the Kerr parameter a, defined as $a = J/M$. Using Boyer-Lindquist coordinates, the position of the horizon of a Kerr black hole is given by

$$r_H = M + \sqrt{M^2 - a^2}\,, \tag{1}$$

which demands the well known constraint $|a| \le M$. For $|a| > M$, there is no horizon and the space-time contains a naked singularity. In absence of horizon, it is possible to reach the physical singularity at $r = 0$

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from some large r in finite time, enter the ring singularity, go to the region with negative values of r, and eventually come back to the starting point at an earlier time. So, the theory allows for the existence of closed time-like curves and causality can be violated.

However, it is widely believed that the Planck scale, $E_{Pl} \sim 10^{19}$ GeV, is the natural UV cut-off of classical general relativity. In other words, the theory would be unable to describe phenomena with a characteristic energy exceeding E_{Pl}. If we apply this general idea to the case of the Kerr space-time with $|a| > M$, where observer-independent quantities like the scalar curvature diverge at the singularity, it is at least questionable to expect that the prediction of the existence of closed time-like curves is reliable. New physics could instead replace the singularity with something else and Nature may conserve causality, not because it is impossible to create an object with $|a| > M$, but because there is no singularity in the full theory. On the basis of this argument, super-spinning Kerr objects with no event horizon, or "super-spinars", might exist in the Universe [5].

3 Accretion process

3.1 Model and assumptions

The first step to study the radiation emitted in the accretion process onto a compact object is to investigate the accretion process itself. In Ref. [6], I discussed the accretion process of a test fluid in a background Kerr space-time; that is, I neglected the back-reaction of the fluid to the geometry of the space-time, as well as the increase in mass and the variation in spin of the central object due to accretion. Such an approximation is surely reasonable to describe the accretion onto a stellar mass compact object in a binary system, because in this case the matter captured from the stellar companion is typically small in comparison with the total mass of the compact object. The results of these simulations should instead not be applied to long-term accretion onto a super-massive object at the center of a galaxy, where accretion makes the mass of the compact object increase by a few orders of magnitude from its original value.

The calculations are made with the relativistic hydrodynamics module of the public available code PLUTO [7], properly modified for the case of curved space-time, as described in [6]. The computational domain is the 2D axisymmetric space $r_{in} < r < 20\,M$ and $0 < \theta < \pi$, where r_{in} is set just outside the event horizon in the case of black hole, and $r_{in} = 0.5\,M$ in the case of super-spinar. The choice of $r_{in} = 0.5\,M$ may appear arbitrary, but it was checked that does not significantly alter the final result for any value of $|a|/M$, as long as $r_{in} \lesssim 0.7\,M$.

Here the accretion process is spherically symmetric and the gas is injected from the outer boundary at a constant rate[2]. Because of the simple treatment of the accreting matter, the gas temperature is not under control. In [6] I simply imposed a maximum temperature: the aim was not to find an accurate description of the accretion process, but to catch some peculiar features of the accretion process onto Kerr objects with $|a| > M$. The code was run with $T_{max} = 10$ keV, 100 keV, and 1 MeV, obtaining essentially the same result. Such a range of T_{max} is the one suggested by observations of galactic black hole candidates: the hard X-ray continuum ($10 - 200$ keV) is a typical feature of all these objects and is often explained with a hot inner disk or a hot corona, in which the electron temperature is around 100 keV (see e.g. Ref. [8]). Let us notice that in this case the accretion process is not the simple Bondi accretion. In the Bondi accretion, the temperature of the gas (ions) at the horizon (in the case of black holes) is about 100 MeV and the proper velocity of the flow is close to 1.

3.2 Results

The results of the simulations are summarized in Fig. 1, where it is shown the rest-mass energy density of the accretion flow around a Kerr black hole with $a/M = 0.9$ (top left panel) and super-spinars with $a/M = 1.1$ (top right panel), 1.4 (bottom left panel), and 2.0 (bottom right panel). The peculiar feature of the case with $|a|/M > 1$ is that the gravitational force near the massive object can be repulsive.

There are three qualitatively different cases determined by the value of $|a|/M$ (for more details, see Ref. [6]):

[2] Spherical or quasi-spherical accretion flows are expected when the compact object accretes from the stellar medium or when it belongs to a binary system in which the companion is massive and has a strong stellar wind.

1) Black hole with $|a|/M \leq 1$. We have the usual accretion picture: the injected matter always reaches a quasi-steady state configuration, in which matter is lost behind the event horizon at the same rate as it enters the computational domain.
2) Super-spinars with $|a|/M > 1$. The gravitational force in the neighborhood of the center $r = 0$ can be repulsive (because of the singularity, not of the rotation of the gas) and thus makes the accretion process harder. The critical radius where the gravitational force changes from attractive to repulsive can be estimated analytically. In Boyer-Lindquist coordinates, it is roughly determined by the sign of the quantity $r^2 - a^2 \cos^2\theta$, i.e. the force is attractive (repulsive) if $r^2 - a^2 \cos^2\theta > 0$ (< 0), where θ is the polar angle[3]. There are two different super-spinar regimes:
2a) Super-spinars with $|a|/M < 1.4$. The accretion process is extremely suppressed and only a small amount of the accreting gas can reach the center. Most of the gas is accumulated around the object, forming a high density cloud that continues to grow. Apparently, no quasi-steady state exists.
2b) Super-spinars with $|a|/M \geq 1.4$. In this case the repulsive force is not capable of preventing a regular accretion of the object. The flow reaches the center by forming a sort of high density disk on the equatorial plane. A quasi-steady state configuration is possible.

The origin of the critical value $|a|/M = 1.4$ can be understood with an analytical argument, as the maximum value for which there are stable marginally bound orbits on the equatorial plane with zero angular momentum at infinity.

4 Final remarks

It is widely believed that the final product of the gravitational collapse of matter is a Kerr black hole. However such a conclusion is based on a set of unproved assumptions, including the Cosmic Censorship Conjecture. In this talk I discussed the possibility that the Cosmic Censorship Conjecture can be violated and I presented some astrophysical implications. I showed that the accretion process in Kerr space-time onto objects with event horizon (black holes) and without event horizon (super-spinars) is quite different and hopefully the two scenarios can be distinguished observationally with no model-dependent assumptions.

Two comments are in order here. First, if the Cosmic Censorship Conjecture is violated, there is no uniqueness theorem guaranteeing that the space-time is described by the Kerr metric. And indeed other axisymmetric solutions of the Einstein equations in vacuum with naked singularities are known (e.g. the Weyl space-times). Here I discussed the case of super-spinar because it is likely the simplest example. Second, we do not know if super-spinars are stable objects and this question is presumably difficult to address, because we do not know how the singularity is solved in the full theory.

The study of the accretion process onto objects with and without event horizon is the first step to figure out possible observational signatures of the radiation emitted in the accretion process which can be used to test the Cosmic Censorship Conjecture. For example, an application of this work will be the predictions of the "direct image" of super-spinars [9, 10].

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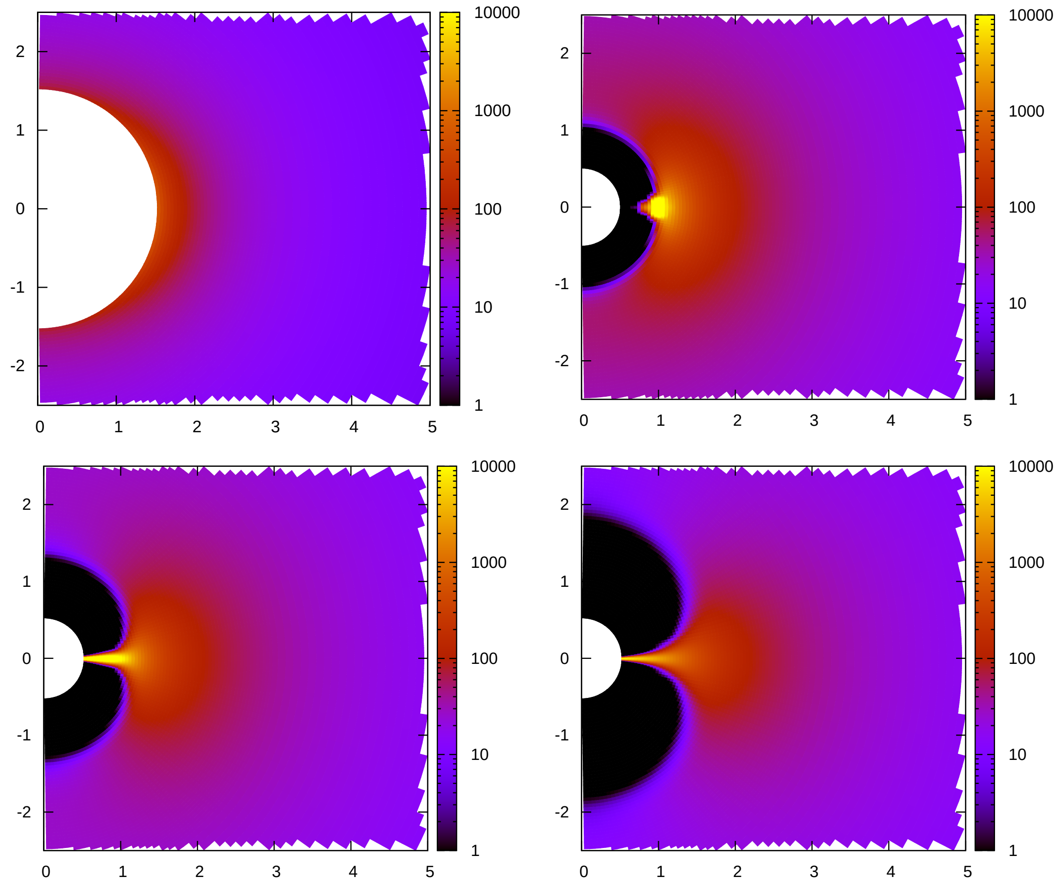

Figure 1: Density plot of the accretion flow around a Kerr BH with $a_* = 0.9$ (top left panel) and super-spinars with $a_* = 1.1$ (top right panel), $a_* = 1.4$ (bottom left panel), and $a_* = 2.0$ (bottom right panel). The density scale (shown on the right hand side of each panel) is in arbitrary units. The unit of length along the x and y axes is M. The white area is out of the domain of computation. The peculiar feature of the super-spinar case is that most of the space-time around the central object is almost empty (the black regions in the pictures): that is the result of the repulsive force at short distance from the center. For more details, see Ref. [6].

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